



# Changes in soil surface chemistry after fifty years of tillage and nitrogen fertilization



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## ABSTRACT

Knowledge gained on the long-term effects of crop management practices on soil fertility is critical in developing nutrient management strategies to optimize crop yields. This study examined the long-term effects of nitrogen (N) fertilizer application rates (0, 22, 45 and 67 kg N ha<sup>-1</sup>) and tillage intensity [conventional tillage (CT), reduced tillage (RT) and no-tillage (NT)] on soil phosphorus (P), micronutrients and soil acidity in a dryland winter wheat (*Triticum aestivum* L.) – sorghum (*Sorghum bicolor* L.) – fallow cropping system. Results showed soil organic matter (SOM), iron (Fe) and manganese (Mn) concentrations were greater under NT compared to CT or RT. Similarly, NT (32 mg kg<sup>-1</sup>) increased P accumulation in the upper 7.5 cm soil depth compared to CT (21 mg kg<sup>-1</sup>) or RT (26 mg kg<sup>-1</sup>). After 50-yr of tillage and N fertilizer application, pH at the soil surface (0 to 7.5 cm) declined markedly with increasing N application, ranging from 6.4 with the unfertilized control to 5.7 when 67 kg N ha<sup>-1</sup> was applied. Averaged across N rates, Δ pH in the soil surface over the 50-yr was greater with NT compared to CT or RT treatments. Iron and Mn concentrations increased with increasing N application rates, possibly due to the decrease in pH associated with N application. Based on our findings, growers adopting NT need to monitor changes in soil surface chemistry and take necessary corrective measures such as liming to maintain satisfactory pH and nutrients levels to optimize crop yields.

## 1. Introduction

Dryland farmers in the semi-arid environment of the central Great Plains region of the USA are increasingly adopting conservation tillage practices such as no-tillage (NT). In 2012, there were 111.5 million ha of planted cropland in the USA, out of which an estimated 38.6 million ha (~35% of total planted acreage) were under NT practices (USDA NASS, 2012). Previous research documented the benefits of NT practices such as reduced soil erosion and runoff (Dick et al., 1991; Baveye et al., 2011; Singh et al., 2012), improved soil physical properties (Blanco-Canqui et al., 2010; Jin et al., 2011), enhanced soil organic matter (SOM) content (Thomas et al., 2007; Blanco-Canqui and Lal, 2008; de Santiago et al., 2008; Kumar et al., 2012), and increased soil water retention (Unger, 1984; Peterson et al., 1996; Stone and Schlegel, 2006; Nielsen and Vigil, 2010). In the Great Plains region of the USA, adoption of NT is credited for reducing wind and water erosion specifically in dryland cropping systems (Hansen et al., 2012).

Despite the benefits mentioned earlier, continuous NT practice tends to cause soil nutrients and SOM stratification (Dick et al., 1991; Guzman et al., 2006; Thomas et al., 2007; Deubel et al., 2011; Mikha

et al., 2013), increase acidification in the upper soil surface (Franzluebbers and Hons, 1996; Duiker and Beegle, 2005; Limousin and Tessier, 2007; Tarkalson et al., 2006; Lopez-Fando and Pardo, 2009), and may increase bulk density near the soil surface (Wander and Bollero, 1999; Halvorson et al., 2002; Zuber et al., 2015). Unlike NT, in conventional tillage (CT) or reduced tilled (RT) practices, soil inversion and mixing with the lower depth (the depth of tillage) through tillage operations could reduce nutrients stratification, bulk density, and soil acidity. The incorporation of crop residue with CT and RT enhances residue decomposition rate depending on the local climate, depth of tillage, and residue incorporation which could lead to SOM depletion (Beare et al., 1994; Paustian et al., 1997; Mikha et al., 2014). Whereas, in NT systems, the accumulation of crop residue at the surface leads to SOM build-up and stratification of nutrients and SOM compared to CT or RT systems.

Tillage effects on soil nutrients distribution within the soil profile specifically for less mobile nutrients such as phosphorous (P), potassium (K), or calcium (Ca) is well documented (Guzman et al., 2006; Thomas et al., 2007; Houx et al., 2011). However, P and K concentrations tend to be greater in the upper 15 cm of soils under NT compared

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to RT or CT systems (Dick, 1983; de Maria et al., 1999; Guzman et al., 2006; Costa et al., 2010; Deubel et al., 2011). Houx et al. (2011) observed that NT resulted in greater accumulation of P and K concentrations in 0 to 5 cm soil depth when compared to CT. However, the accumulation of P and K concentration below 5 cm depth associated with NT was observed to be less or similar to that under CT, suggesting significant nutrient stratification in the NT compared with CT. Tillage effects on micronutrients, iron (Fe), Zinc (Zn), copper (Cu) and manganese (Mn) distribution in the soil is less consistent. Previous studies reported greater accumulation of micronutrients, particularly Zn and Mn in upper surface of soils under NT (Edwards et al., 1992; Franzluebbers and Hons, 1996; Martin-Rueda et al., 2007; de Santiago et al., 2008; Moreira et al., 2016), yet others found tillage had no effect on Zn and Mn availability in the soil (Lavado et al., 1999; Hickman, 2002).

The combination of different tillage practices and fertilizer management were found to affect soil chemical properties at different depths (Blevins et al., 1983; Schroder et al., 2011). Soil acidification was significantly greater in the upper soil surface under NT compared to CT systems, but the decrease in pH was exacerbated with increasing N rate regardless of tillage intensity (Blevins et al., 1983; Fageria et al., 2010; Das et al., 2012). In a long-term (30-yr) study in Oklahoma, Schroder et al. (2011) found a significantly negative relationship between soil pH and the amount of N fertilizer applied regardless of N source. Soil acidification near the soil surface is usually caused by nitrification of ammonium containing fertilizers and decomposition of SOM (Barak et al., 1997; Bolan and Hedley, 2003; Fageria et al., 2010).

Soils in the central Great Plains region of USA are general calcareous with high buffering to changes in pH due to the semi-arid climate that limit leaching of basic cations (Soil Survey Staff, 2016). However, recent adoption of no-till coupled with intensified crop production systems that required inorganic N fertilizer application to achieved optimum grains yields can result in soil acidification. In a dryland NT wheat-corn (*Zea mays*)-fallow rotation study in Colorado, USA, Bowman and Halvorson (1998) found a significant decrease in pH from 6.5 to 5.1 at the surface 5 cm after nine annual applications of ammonium nitrate at  $112 \text{ kg N ha}^{-1}$ . This decrease in soil pH can reduce nutrient availability and uptake and may also cause plant injury. Long-term experiments are needed to investigate soil management effects on soil chemistry and nutrient dynamics to aid in developing nutrient management strategies to optimize crop yields.

Few studies have investigated the effects of long-term (> 20-yr) tillage and N fertilizer management on soil chemistry in semi-arid dryland crop production systems (Thompson and Whitney, 2000; Tarkalson et al., 2006). In a 30-yr tillage and N fertilizer application study on a silt loam soil in Kansas, Thompson and Whitney (2000) found significant decline in soil pH and extractable P concentration in the upper 7.5 cm of the soil with increasing N fertilizer application rate. Regardless of tillage intensity, soil pH in the upper 7.5 cm increased in the control treatment compared to the initial soil test levels. In addition, the authors showed P and SOM concentrations were greatest near the soil surface with NT when compared to soils under CT or RT plots. Due to lower precipitation amounts, changes in soil chemistry in semi-arid dryland systems may take longer time compared to environments with greater precipitation. To our knowledge, long-term soil management effects on nutrient dynamics, particularly micronutrients has not been extensively studied in the semi-arid Great Plains. The current manuscript is a follow up of the findings by Thompson and Whitney (2000) to examine soil profile distribution of pH and soil nutrients after 50-yr of tillage and N fertilizer application to a Typic Agriustoll soil. We hypothesized that soil acidification and SOM accretion will be confined to the surface of soils under long-term no-till production. The objective of the current study was to investigate changes in soil chemical properties within 0 to 60 cm of the soil after 50-yr of tillage and nitrogen applications to a wheat-sorghum-fallow (W-S-F) crop rotation system in the semi-arid central Great Plains.

## 2. Materials and methods

### 2.1. Site description

This long-term study was conducted at the Kansas State University Agricultural Research Center near Hays, Kansas ( $38^{\circ}86' \text{ N}$ ,  $99^{\circ}27' \text{ W}$ , 609 m elevation) on a Harney silt loam soil (fine, montmorillonite, mesic Typic Agriustoll). The Harney series consists of deep, well-drained soils formed in calcareous, medium-textured loess, and has slopes of 0–7% (Soil Survey Staff, 2016). Long-term average annual precipitation at the experimental site is 560 mm, of which > 75% (438 mm) is received from April through September. Mean annual air temperature is  $12^{\circ} \text{ C}$ .

Soil fertility analysis conducted at the beginning of the study in 1965 was not different among the preassigned crop rotation and tillage treatment plots. Average soil pH in the upper 0 to 7.5 cm of the soil was 6.3, extractable P was  $62.5 \text{ mg kg}^{-1}$ , and SOM was  $2.1 \text{ g kg}^{-1}$ . Similarly, soil pH measured at 7.5 to 15 cm depth was 6.6, while P and SOM concentrations were  $40.1 \text{ mg kg}^{-1}$  and  $1.9 \text{ g kg}^{-1}$ , respectively. Prior to the initiation of the study in 1965, the experimental site was managed as a CT wheat-fallow crop production system.

### 2.2. Study set-up and treatments

The study was established in 1965 to investigate the effects of tillage intensity on winter wheat and grain sorghum yields in a W-S-F rotation scheme. The three tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) arranged in randomized complete blocks with four replications. Each phase of the W-S-F crop rotation was present in each year of the study. Then in 1975 the experiment was modified to superimposed N fertilizer application rates to the tillage treatments in a split-plot arrangement. The original tillage treatments (CT, RT, and NT) were the main plots and sub-plot factor was four N application rates (0, 22, 45 and  $67 \text{ kg N ha}^{-1}$ ). Individual plot sizes of each tillage treatment were  $20.4 \text{ m} \times 30.5 \text{ m}$ , which were the split into four  $3.4 \text{ m} \times 30.5 \text{ m}$  sub-plots to accommodate the N application rate treatments. There was a 3.5 m wide border between tillage treatments. Ammonium nitrate was the N fertilized source from 1975 to 2002, thereafter; urea was the N fertilizer source applied to the plots. Nitrogen fertilizer was broadcasted in the fall prior to wheat planting while N application to grain sorghum plots were done in early spring before sorghum planting in June. Fertilizer was incorporated in the CT and RT tilled plots while fertilizer applied remained on the soil surface under NT. Because soil test levels for available P were medium to high over the study period and exchangeable potassium (K) are inherently high in this soil, therefore, N was the only fertilizer applied over the 50-yr study period.

### 2.3. Crop management

The W-S-F cropping system starts with winter wheat planted in late September to the first week in October and harvested the following June or July. The cropland is left fallow after wheat harvest then planted to grain sorghum the following year in June and harvested in November. The land remains fallow until the following September or October when it is planted again to winter wheat. This W-S-F cropping system allows production of two crops in 3-yr with a 10 to 11-month fallow period between grain sorghum and winter wheat crops. Details of all field operations and crop management are presented in Thompson and Whitney (2000). Briefly, the CT plot were plowed and disked to 15 cm soil depth to incorporate crop residue using a tandem disk. In addition, a field cultivator was used for the last tillage operation before wheat planting. However, tillage in the RT treatments was done with a sweep plow. Tillage operations with a sweep plow doesn't involve soil inversion therefore significant amount of crop residue are left on the soil surface compared to disking and plowing in the CT plots.

**Table 1**  
Analysis of variance summary of tillage and N fertilizer rates effects on soil organic matter (SOM), pH, phosphorus (P), Nitrate-N (NO<sub>3</sub>-N), exchangeable calcium (Ca), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn) and zinc (Zn) in soil samples collected within 0 to 60 cm in 2015.

Effects	pH	Δ pH	SOM	Δ SOM	P	Δ P	NO <sub>3</sub> -N	K	Ca	Mg	Fe	Mn	Zn
Tillage (T)	0.1975	<b>0.0262</b>	<b>0.0029</b>	< <b>0.0001</b>	0.399	0.2197	<b>0.0105</b>	0.5642	<b>0.0015</b>	0.1344	0.215	0.6184	0.1647
N rate (N)	<b>0.0247</b>	0.3126	0.6604	0.6013	0.7835	0.8566	< <b>0.0001</b>	0.1141	0.8606	0.408	<b>0.0016</b>	<b>0.0003</b>	0.3482
T × N	0.5022	0.6528	0.5936	0.5117	0.3798	0.4539	0.1709	0.6125	0.4262	0.3907	0.9326	0.8737	0.2046
Depth (D)	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>	< <b>0.0001</b>
T × D	0.2459	0.5587	< <b>0.0001</b>	0.2338	<b>0.0014</b>	<b>0.0227</b>	<b>0.0021</b>	0.0608	0.3703	0.1809	<b>0.0037</b>	<b>0.0157</b>	0.6404
N × D	< <b>0.0001</b>	<b>0.0504</b>	0.3847	0.2118	0.9219	0.7221	<b>0.0012</b>	0.1351	0.8297	0.8806	< <b>0.0001</b>	< <b>0.0001</b>	0.4972
T × N × D	0.6596	0.7945	0.9888	0.9661	0.381	0.3792	0.665	0.4366	0.8673	0.4156	0.9755	0.4751	0.5642

Treatment effects in bold are significant at  $P \leq 0.05$ .

Approximately 3 to 4 tillage operations were performed in the fallow phase prior to winter wheat planting in CT while 2 operations occurred in the RT plots. One tillage operation was usually conducted in both CT and RT plots prior to sorghum planting. Only herbicides were used for weed control in the NT plots. Weed control during the growing season and fallow periods were accomplished with appropriate herbicides as needed across all tillage practices.

#### 2.4. Soil sampling and analysis

Soil samples were collected at the beginning of the study in the fall of 1965 and in 1995. Three soil cores (2.5 cm diam.) were collected randomly from each plot at 0 to 7.5 cm and 7.5 to 15 cm soil depths at both sampling times. The soil samples were air-dried, crushed and sieved through a 2-mm sieve and then analyzed for soil pH, SOM and P concentration at the Kansas State University soil testing laboratory. These soil analysis data were published previously (Thompson and Whitney, 2000). Soil samples were taken again in May 2015 in the fallow phase to determine changes in soil chemical properties after 50-yr of tillage and N fertilization. Three soil cores (2.5 cm diam.) were randomly collected in each plot from 0 to 7.5, 7.5 to 15, 15 to 30, and 30 to 60 cm soil depth. The samples were composited per depth for each plot, air-dried, crushed, and sieved to pass through a 2-mm stainless steel screen.

The sieved soil samples were then analyzed for pH and soil extractable nutrients at the Kansas State University soil testing laboratory using standard soil testing procedures (Leikam et al., 2003). Briefly, pH and electrical conductivity were determined potentiometrically by an electrode (Thomas, 1996). Available P was determined by Mehlich-3 extraction method (Mehlich, 1984), and P concentration following extraction was measured using inductively coupled plasma-optical emission spectrometry (ICP-OES), exchangeable Ca, Mg, and K concentration were determined on an ICP-OES after NH<sub>4</sub>OAc extraction (Knudsen et al., 1982), Fe, Mn and Zn were extracted with the DTPA extraction (Lindsay and Norvell, 1978) and nutrient concentration measured using atomic absorption spectrometry. Soil organic matter was determined by a modified Walkley-Black procedure (Nelson and Sommers, 1996). To determine treatments effects on soil organic carbon (SOC) concentration, additional soil samples were taken at 0–5, 5–15, 15–30 and 30–60 cm depths. The samples were air-dried, ground, and sieved through 0.25 mm sieve. The SOC concentration was determined by dry combustion using a CN analyzer after pretreating samples with 10% (v/v) HCl to removed carbonates (Nelson and Sommers, 1996). Changes in soil pH, SOM and P concentration over the 50-yr within 0 to 15 cm soil depth were computed by difference between concentrations measured in 2015 and that of 1965.

#### 2.5. Statistical analysis

Data were subjected to ANOVA as a split-plot design using the PROC MIXED procedure of SAS ver. 9.2 (SAS Institute, 2006). Tillage, N application rates and soil sampling depth were the fixed effects while replications and their interactions were considered random effects. The LSMEANS procedure of PROC MIXED along with adjusted Tukey was used for mean comparisons. Interactions and treatment effects were considered significant when  $F$  test  $P$  values were  $\leq 0.05$ . Regression analyses were conducted with the Proc Reg procedure in SAS to determine the relationship between soil pH and micronutrient availability.

### 3. Results

#### 3.1. Grain yield

Grain yield data from this long-term experiment has been previously published by Thompson and Whitney (1998) and Obour et al. (2015),

so that data will not be discussed in the present paper. Briefly, grain yields with NT were significantly lower than CT and RT at the lower N application rates of 22 and 45 kg N ha<sup>-1</sup>. However, at 67 kg N ha<sup>-1</sup> grains yields were not different among the tillage treatments. Irrespective of tillage treatments, wheat and grain sorghum yields increased with increasing N fertilizer application rates. In addition, average wheat and sorghum yields with RT were equal or greater than CT in most years at each N rate (Thompson and Whitney, 1998; Obour et al., 2015).

### 3.2. Soil pH and soil organic matter

Nitrogen application ( $P = 0.03$ ) and N rate  $\times$  sampling depth interaction had significant ( $P < 0.0001$ ) effects on soil pH. Averaged across tillage treatments, N application at 67 kg N ha<sup>-1</sup> significantly decreased soil pH in the top 7.5 cm compared to the lower N rates. However, beyond this depth, pH was not different among the N application rates (Table 2). Over the 50-yr, the change in soil pH at the top 0 to 15 cm depth was significantly affected tillage and N rate  $\times$  depth interaction (Table 1). Across tillage treatments, soil pH at the surface 0 to 7.5 cm change little in the unfertilized check but decreased 0.6 units when 67 kg N ha<sup>-1</sup> was applied. Similarly, across N rate and sampling depth, pH within 0 to 15 cm decreased 0.8 unit with NT, greater than the 0.3 or 0.2-unit decrease in CT or RT (Table 3).

Nitrogen application had no effect ( $P = 0.66$ ) on SOM concentration. However, tillage and tillage  $\times$  sampling depth interaction ( $P < 0.0001$ ) all had effect on SOM concentration (Table 1). In general, tillage effect on SOM concentration was limited to the top 0 to 30 cm soil depth. Averaged across N application rates, SOM concentration with NT and RT were not different but were both greater than that measured under CT (Table 3) within the top 30 cm depth. Beyond this depth, SOM concentration were similar among the tillage treatments. Tillage  $\times$  sampling depth interaction ( $P = 0.0002$ ) affected SOC concentration. Average across N rates, SOC concentration in the top 5 cm of the soil with NT was 21 g kg<sup>-1</sup>, greater than that with CT (16 g kg<sup>-1</sup>) and RT (17 g kg<sup>-1</sup>) when averaged across N application rates (Fig. 1a). Below 5 cm depth, SOC tended to be greater with NT but was not significantly different from that of CT or RT treatments. Similarly, SOC concentration was significantly affected by sampling depth  $\times$  N application rate interaction ( $P = 0.0007$ ). This occurred because increasing N application did increase SOC in the top 5 cm of soil. However, N application had no effect on SOC concentration at deeper soil depths (Fig. 1b).

### 3.3. Nitrate-N and extractable soil nutrients

Tillage  $\times$  depth and N rate  $\times$  depth interaction had effect on residual NO<sub>3</sub>-N concentration measured in 2015 (Table 1). Across N rates, NO<sub>3</sub>-N concentration measured within 0 to 30 cm depth in soils under CT or RT were greater than that of NT. Beyond 30 cm, NO<sub>3</sub>-N concentration was similar among the tillage treatments (Table 3). Averaged across tillage system, increasing N application resulted in significant NO<sub>3</sub>-N accumulation in the top 0 to 15 cm soil depth (Table 2). Nitrogen application had no effect on NO<sub>3</sub>-N concentration beyond 15 cm depth. The extractable P concentration measured in 2015 was affected by tillage  $\times$  sampling depth interaction (Table 1). Phosphorus concentration in the upper 7.5 cm of soil under NT was 32.1 mg kg<sup>-1</sup>, greater than P concentrations under CT (20.7 mg kg<sup>-1</sup>) or RT (26.2 mg kg<sup>-1</sup>) measured at this depth (Table 3).

Tillage treatments had significant effect on exchangeable Ca concentration (Table 1). Averaged across N rate and sampling depth, Ca concentration with CT (3960 mg kg<sup>-1</sup>) or RT (4220 mg kg<sup>-1</sup>) were greater than the 3794 mg kg<sup>-1</sup> measured in soils under NT. However, K and Mg concentrations were not affected by either tillage or N application rate (Table 1). The concentrations of these nutrients differed between the sampling depths. Averaged across tillage treatments and N

application rates, K concentration in the upper 7.5 cm was 564 mg kg<sup>-1</sup>, greater than the 546 mg kg<sup>-1</sup> measured in the lower 7.5 to 15 cm, 480 mg kg<sup>-1</sup> at 15 to 30 cm or 463 mg kg<sup>-1</sup> at the 30 to 60 cm depth. Magnesium concentration tended to be greater in the subsoil compared to the upper 7.5 cm depth. Average Mg concentration was 395 mg kg<sup>-1</sup> in the top 7.5 cm < 466 mg kg<sup>-1</sup> measured in the 7.5 to 15 cm depth, 593 mg kg<sup>-1</sup> at 15 to 30 cm, or 623 mg kg<sup>-1</sup> measured at 30 to 60 cm depth.

### 3.4. Micronutrients: Fe, Mn and Zn

Tillage  $\times$  sampling depth interaction had effect on Fe and Mn concentrations measured in 2015 (Table 1). However, Zn concentration was not influenced by either tillage or N fertilizer application rate (Table 1). Tillage effects on Fe concentration were mostly limited to the surface soil. Averaged across N rates, Fe concentration in the upper 0 to 7.5 cm ranged from 25.9 mg kg<sup>-1</sup> with CT to 34.6 mg kg<sup>-1</sup> under N (Table 3). Similarly, Mn concentration was greater with NT compared to the other tillage treatments in the upper 7.5 cm depth. At 7.5 to 30 cm, Mn concentration with CT was less than that measured under RT or NT. However, at the 30 to 60 cm depth, Mn concentration was similar among the three tillage systems (Table 3).

The interaction of sampling depth  $\times$  N application significantly affected soil Fe and Mn concentration but not Zn (Table 1). Both Fe and Mn concentrations in the upper soil surface (0 to 7.5 cm) increased with increasing N fertilizer application rate (Table 2). Averaged across tillage treatments, Fe concentration with 67 kg N ha<sup>-1</sup> was two-fold greater than that of the unfertilized check at the soil surface. Similarly, Mn concentration ranged from 24.2 mg kg<sup>-1</sup> with the no N fertilizer treatment to 37.0 mg kg<sup>-1</sup> when 67 kg N ha<sup>-1</sup> was applied (Table 2). Conversely, Fe and Mn concentrations below 7.5 cm soil depth were not different among the N application rates.

## 4. Discussion

### 4.1. Tillage effects

Results supported our hypothesis, suggesting the lower precipitation amount received in the semi-arid USA Great Plains may confine changes in soil pH and nutrient accumulation to the upper soil layer with limited movement to the subsoil. In the present study, tillage had effect on changes in pH, SOM and P concentration over the 50-yr but also on Fe and Mn concentrations measured in the top 15 cm in 2015. Over the 50-yr study,  $\Delta$  pH in soils under long-term NT was 0.8 units, > 0.3 and 0.2 units decrease associated with CT and RT, respectively (Table 3). This is consistent with previous findings that showed a decrease in soil surface pH under NT compared with tillage treatments (Franzuebbers and Hons, 1996; Tarkalson et al., 2006; Limousin and Tessier, 2007; Lopez-Fando and Pardo, 2009; Houx et al., 2011). In NT systems, mineralization of SOM and nitrification of applied N fertilizer occurs on the soil surface that can result in a significant decrease in pH at the soil surface. However, tillage operations employed in CT or RT incorporate and mix fertilizer with a larger soil volume. Besides, mixing and redistribution of soil from the subsoil with relatively greater pH and concentrations of Ca and Mg through tillage operations will provide some buffering against pH changes in soils under CT or RT. Our results also showed SOM concentration increased in the upper 15 cm of soil after 50-yr of the study. This increase in SOM concentration between 1965 and 2015 ranged from 3.8 g kg<sup>-1</sup> under CT to 12.0 g kg<sup>-1</sup> with RT and 11.8 g kg<sup>-1</sup> with NT (Table 3), corresponding to 21% increase in SOM with CT and 58% increase in SOM concentration with soils under NT or RT. These differences were due to elimination or reduction in tillage operations which reduced soil disturbance and SOM decomposition resulting in greater crop residue and significant SOM accretion under NT and RT in the present study. The increase in SOM concentration with CT compared to the 1965 levels is

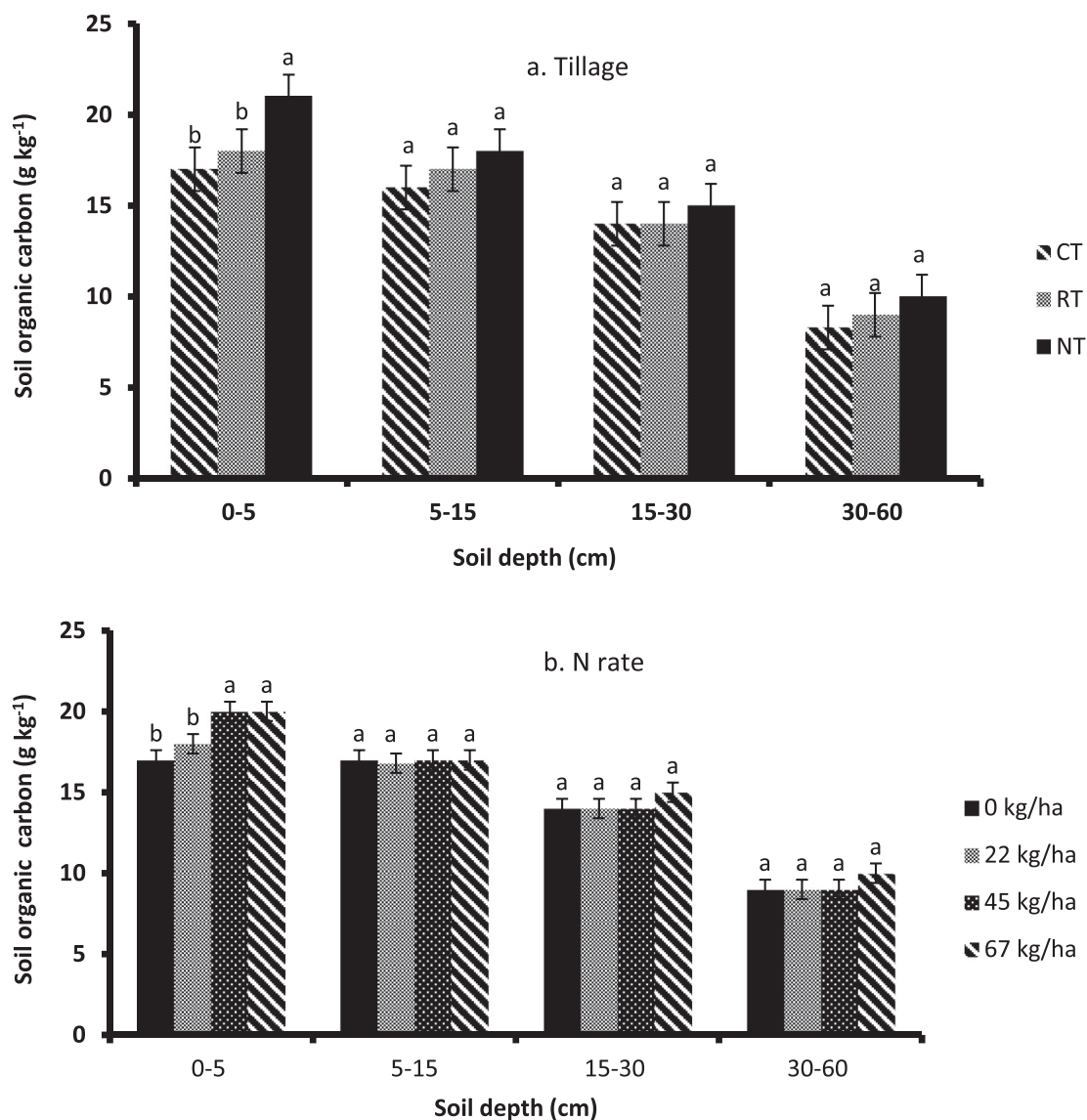


Fig. 1. Soil organic carbon concentration measured in 2015 as affected by (a) tillage  $\times$  sampling depth (b) N application rate  $\times$  sampling depth. Error bars represent one standard error of the mean. Means followed by the same letter (s) within a soil depth are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ( $P > 0.05$ ).

Table 2

Soil pH, nitrate-N, iron and manganese concentrations measured in 2015 as affected by nitrogen fertilizer application rate and soil sampling depth.

N rate	pH				Nitrate-N			
Kg ha <sup>-1</sup>	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm
0	6.43 a*	6.64 a	7.21 a	7.70 a	6.4 c	4.6 c	4.2 a	1.9 a
22	6.28 a	6.50 a	7.11 a	7.74 a	10.5 b	7.2 b	5.4 a	2.8 a
45	6.31 a	6.53 a	7.19 a	7.69 a	12.2 b	8.5 ab	5.2 a	3.3 a
67	5.72 b	6.47 a	7.24 a	7.77 a	16.3 A	10.3 a	6.3 a	3.9 a
	Iron				Manganese			
					mg kg <sup>-1</sup>			
0	18.5 d	16.9 a	22.3 a	20.2 a	24.2 c	19.6 a	15.3 a	7.2 a
22	23.5 c	18.1 a	24.4 a	20.8 a	29.9 b	21.3 a	17.4 a	7.4 a
45	31.6 b	20.6 a	24.0 a	21.4 a	31.6 b	22.2 a	15.8 a	7.3 a
67	38.3 a	19.9 a	22.9 a	19.2 a	37.0 a	21.0 a	14.6 a	6.8 a

\* Means followed by same letter (s) within a tillage system are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ( $P > 0.05$ ). Data are averaged across three tillage treatments and four replicates ( $n = 12$ ).

**Table 3**

Soil pH, soil organic matter (SOM), phosphorus (P), Nitrate-N, iron and manganese concentrations measured in 2015 as affected by tillage and soil sampling depth.

Tillage/depth	Soil organic matter				Phosphorus			
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm
	g kg <sup>-1</sup>				mg kg <sup>-1</sup>			
CT	23.5 b <sup>*</sup>	24.0 b	19.5 b	14.1 a	20.7 c	6.8 a	4.9 a	7.4 a
RT	30.9 a	33.3 a	20.9 ab	15.7 a	26.2 b	8.4 a	4.6 a	6.5 a
NT	31.3 a	32.3 a	22.0 a	15.8 a	32.1 a	5.3 a	4.6 a	5.7 a
	Iron				Manganese			
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm
	mg kg <sup>-1</sup>							
CT <sup>§</sup>	25.9 b	17.1 a	21.3 a	21.6 a	30.3 b	19.2 b	13.7 b	6.4 a
RT	23.4 b	19.1 a	23.9 a	19.2 a	28.0 b	21.8 a	16.9 a	7.4 a
NT	34.6 a	20.5 a	25.0 a	20.4 a	33.7 a	22.1 a	16.7 a	7.7 a
	Nitrate-N				Δ P <sup>†</sup>			
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	0–7.5 cm	7.5–15 cm	0–15 cm	0–15 cm
	mg kg <sup>-1</sup>				g kg <sup>-1</sup>			
CT	14.3 a	10.1 a	6.9 a	3.6 a	–41.8 a	–33.2 a	–0.25 b	3.8 b
RT	13.1 a	8.3 a	5.7 a	3.1 a	–36.3 b	–31.7 a	–0.23 b	12.0 a
NT	6.7 b	4.5 b	3.3 b	2.2 a	–30.6 c	–34.7 a	–0.75 a	11.8 a

<sup>\*</sup> Means followed by same letter (s) within a tillage system are not significantly different using the least squares means (LSMEANS) and adjusted Tukey multiple comparison procedure ( $P > 0.05$ ). Data are averaged across four nitrogen rates and four replicates ( $n = 16$ ).

<sup>§</sup> CT = Conventional tillage; RT = Reduced tillage; NT = NO-tillage.

<sup>†</sup> Δ pH = difference between pH measured in 2015 and 1965; and Δ SOM = difference between SOM measured in 2015 and 1965.

probably due to cropping intensification by shifting from wheat-fallow (prior to 1965) to wheat-sorghum-fallow system that added more crop residue to the soil.

Tillage effect on P distribution was only significant in the surface 0 to 7.5 cm and was greater in soils under NT. This observation was expected because P is relatively immobile within the soil and tends to accumulate on the soil surface in NT systems where there are no tillage operations to incorporate crop residue and redistribute P to deeper soil layers. In this study, the significant reduction in soil P with CT and RT at 0–7.5 cm was associated with slight increase in soil P at the 7.5–15 cm depth compared with NT. The differences in soil P associated with different depths were due to tillage operation and soil mixing up to 15 cm depth for CT and RT treatments. Similar to the present study, Thomas et al. (2007) found greater extractable P concentration under NT than with CT or RT in the upper 0 to 10 cm of the soil, but tillage effects on P concentration below 10 cm were not significantly different. Other researchers (Dick, 1983; Fernandez et al., 2008; Houx et al., 2011) have reported greater P accumulation and stratification in the upper surface of soils under NT. Notwithstanding, after 50-yr of tillage and N fertilizer application, P concentrations measured in the upper 15 cm of the soil declined markedly regardless of tillage intensity. This decrease in P concentration compared to the 1965 levels was expected because no P fertilizer were applied over the 50-yr of the study. Crop removal without replenishment from P fertilization accounted mostly for the decline in P concentration and not tillage effects. However, differences in P cycling among the tillage treatments affected the rate of decline in P concentration under each tillage system. For instance, in the top 7.5 cm of the soil, P concentration with CT decreased by 41.8 mg kg<sup>-1</sup> relative to the 1965 levels. This was greater than a decrease of 36.3 mg kg<sup>-1</sup> with RT or 30.6 mg kg<sup>-1</sup> observed under NT (Table 2). Beyond 7.5 cm, the decrease in soil P concentration was similar among the tillage treatments. Average P concentration measured in 2015 in the upper 15 cm were 13.7 mg kg<sup>-1</sup> for CT, 17.3 mg kg<sup>-1</sup> for RT and 18.6 mg kg<sup>-1</sup> with NT. Current Kansas State University fertilizer guidelines recommends P fertilizer application when Mehlich-3 soil test P concentration in the upper 15 cm soil depth is < 20 mg kg<sup>-1</sup> (Leikam et al., 2003). Based on this P fertilizer guideline, P fertilizer required for a 2688 kg ha<sup>-1</sup> winter wheat yield goal will be 28 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> for wheat produced under CT, and 17 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> for wheat that will be planted under RT or NT.

Tillage had effect on exchangeable Ca concentration but not K or Mg concentration. This is in contrast with previous research (Edwards

et al., 1992; Houx et al., 2011) that observed greater soil K, Ca or Mg concentrations at the surface of soils under NT compared to CT or RT. The lack of tillage effects on exchangeable cations observed in the present study is probably due to inherently greater levels of basic cations in soils at the experimental site. In the semi-arid Great Plains, precipitation amounts and low (560 mm in the present study) which limit leaching of basic cations in the soil. It is therefore common to measure greater concentrations of Ca, K and Mg in the upper surface of soils in these environments (Obour et al., 2016). The lower Ca concentration in soils under NT is probably due to increased acidity with NT over the 50-yr. Findings in the present study also showed reducing tillage intensity increased Fe and Mn concentrations in the upper soil surface. The observed differences could be due to differences in SOM concentration among the tillage treatments. This is consistent with others (de Santiago et al., 2008; Aziz et al., 2013; Moreira et al., 2016) who showed greater micronutrient concentrations in soils under NT was due to increase in SOM content associated with NT systems.

#### 4.2. Nitrogen rate effects

Results of the present study showed long-term N fertilizer application could be changing the upper surface chemistry of soils under dryland crop production in semi-arid Great Plains due to decrease in pH associated continue N fertilizer usage. After 50-yr, pH in the top soil surface (0 to 7.5 cm) decreased markedly with increasing N fertilizer application rates. This is consistent with the previous findings by Thompson and Whitney (2000), suggesting soil acidification from N fertilization had not moved beyond 7.5 cm. This is significant because the acidity is confined to the upper surface and may have limited effects on crop growth due to greater soil subsoil pH. Previous research (Bouman et al., 1995; Barak et al., 1997; Schroder et al., 2011) also observed a decrease in soil surface pH with long-term N fertilizer application due to nitrification of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup> when ammonium-containing fertilizers (ammonium nitrate and urea in the present study) are applied. In the present study, increasing N application resulted in greater residual N concentration in the top 0 to 15 cm of the soil (Table 2). This excess residual N from N fertilizer application contributed to soil acidification observed in the N fertilized plots.

Despite the decline in pH, SOC concentration measured at the surface 0 to 5 cm depth increased with N fertilizer rates. This finding agrees with Bowman and Halvorson (1998) who reported a decrease in surface (0–5 cm) soil pH from 6.5 to 5.1 when 112 kg N ha<sup>-1</sup> was

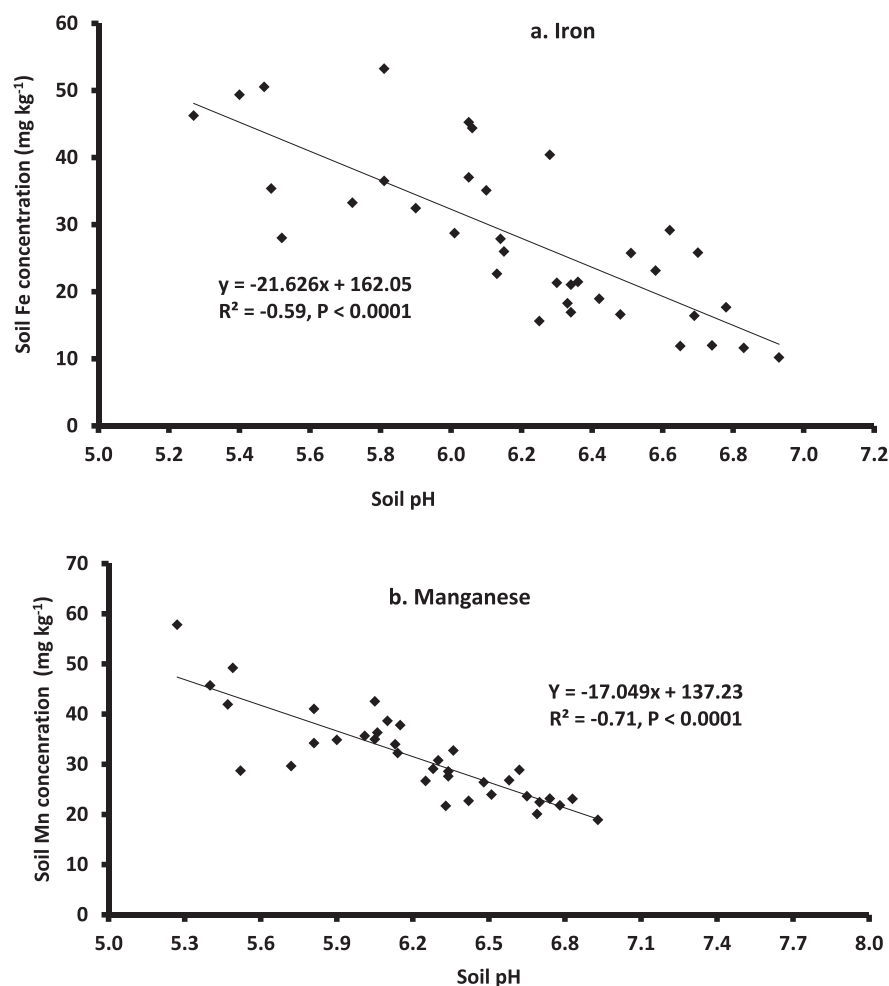


Fig. 2. Relationship of soil pH with iron (a), manganese (b) availability in the upper 7.5 cm of the soil measured in 2015.

applied, however, this was accompanied by a 40% increase in SOC. Although N fertilizer application will increase N availability to enhance microbial activity and decomposition of organic C, applying N fertilizer general increase yields and total biomass produced. In dryland systems, this increase in biomass production will affect amount of residue return and ultimately increase total SOC in the soil. Micronutrients, Fe and Mn concentrations measured after 50-yr of the study at the soil surface increased with N fertilizer application. The increase in Fe and Mn concentrations with increasing N application rates is mostly due to the decrease in pH associated with N application. Regression analysis showed an inverse relationship between pH and soil micronutrient concentrations (Fig. 4). The correlation coefficients of the relationship between soil pH and Fe, and Mn concentrations were 0.59 and 0.71, respectively. Availability of these micronutrient cations (Fe and Mn) increased when the soil pH was slightly acidic to neutral (Fig. 2a and b). Micronutrient availability is reduced at higher soil pH because of the change in ionic form of the cations into metal oxides or hydroxides that are relatively insoluble (Brady and Weil, 2008). Although lowering the soil pH increased micronutrient availability, there is also the potential for nutrient toxicity particularly with Mn. Manganese toxicity is currently not an issue in this long-term plots, but this is something that will be monitored as we continue with the study.

#### 4.3. Summary and conclusion

Results showed decline in soil surface pH in soils under NT over the 50-yr was greater than that with CT or RT systems. Soil organic matter content was similar with NT and RT but were both greater than that measured under CT. Significant accumulation of P occurred in the

upper 7.5 cm of soils under NT compared to CT or RT. Nitrogen application increased SOC content at the soil surface but also resulted in marked decline in soil pH. Soil concentrations of Fe and Mn increased with increasing N application rates, likely due to the decrease in pH associated with N application. Exchangeable K and Mg concentration were not affected by tillage treatments, perhaps due to the inherent high concentrations of these cations in the soil at the study site. Based on our findings, growers adopting NT need to monitor changes in soil surface chemistry and take necessary corrective measures such as liming to maintain satisfactory pH levels to optimize crop yields.

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